MEASUREMENT OF RADIATIVE HEAT TRANSFER WITH THIN-FILM RESISTANCE THERMOMETERS

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ABSTRACT

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The use of a dual-element thin-film resistance thermometer for measuring simultaneously the convective and radiative components of heat transfer rate is described. Resistance elements consist of thin, platinum-alloy films deposited on substrates of fused quartz. Calibration procedures for evaluating the spectral absorption of radiant energy in the wavelength range from 0.8 to 2.6 microns are described. A summary of the test data, applicable to ambient room temperature conditions, is given.

AUTHOR

FOREWORD

This report was prepared for the George C. Marshall Space Flight Center, NASA, under Contract No. NAS-8-823. The work documented herein constitutes a part of a broad program devoted to the study of rocket base heating using short-duration techniques. This total effort is under the overall cognizance of the Aeroballistics Division of MSFC with Messrs. W. K. Dahm and H. B. Wilson, Jr., as technical supervisors.

This report is concerned with the calibration of heat transfer instrumentation used to measure radiative heat transfer on the base heating program.

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INTRODUCTION

Rocket base heating phenomena are being experimentally explored at the Cornell Aeronautical Laboratory (CAL) using short-duration testing techniques based on shock tube principles.[1] A significant fraction of the measured heat flux may be radiative in nature; consequently, a separate measure of this quantity is desirable.

Because of the extensive experience that has been accumulated at CAL in the application and construction of thin-film heat transfer transducers,[2, 3] it was logical to extend the use of these transducers to the sensing of radiative flux. Measurement of radiative heat transfer with thin-film transducers requires an understanding of both the electrical and the optical properties of the film and substrate in the spectral region of interest.

For radiation incident on an optical surface, certain parameters are associated with the reflected and transmitted components. These parameters include intensity, phase, polarization, as well as refraction and absorption which are related to the transmitted energy. All these measurable parameters are dependent upon the wavelength and angle[4] of the incident radiation and are expressible in terms of one or two material constants.[5] For dielectric materials, only the index of refraction n is required for those spectral regions devoid of absorption. For metals, the refractive index is a complex quantity, n - ik, where k is the absorption coefficient. The optical constants n and k are related to the electrical characteristics of the metallic films.[6]

Thus, if the values of n and k are known as functions of wavelength, the absorption, reflection and transmission of the radiant energy incident on the film may be evaluated. The problem exists, however, of assurance that the optical constants do indeed apply to the film in question. In general, the optical constants of materials in the form of thin films are significantly different from those applicable to the same materials in bulk form. These differences are related even to the specific technique of producing the film. Films of a given thickness will be characterized by different optical constants depending on whether they were formed by chemical deposition, sputtering, or evaporation. Evaporated films are further affected by residual gas pressure during evaporation, rate of deposition, and film aging.[5]

INTRODUCTION (Cont'd)

The principal reason underlying the variation of optical properties between bulk and thin-film forms is structure. Thin films tend to be characterized by porosity, aggregation, and small crystalline size.

The unpredictable optical characteristics of thin films therefore necessitate that calibration tests be performed if a meaningful interpretation of the base heating data is to be made. Of prime interest is the spectral absorption of the thin-film resistance thermometer.

This report describes the radiative heat transfer transducer and presents the details of the calibration experiments performed to assess the spectral absorption characteristics. Absorption data were inferred from direct measurements of transmission and reflection in the spectral interval from 0.8 to 2.6 microns.

RADIATIVE HEAT TRANSFER GAGES

The heat transfer gage resistance elements are platinum-alloy films, approximately four microinches thick, which are deposited on suitable substrates by brushing on a platinum solution* and firing the units in a furnace. Planform dimensions of the elements approximate 0.030-inch by 0.25-inch and result in room temperature resistances of 75 to 125 ohms. Silver tabs are deposited at the terminals of these film strips and function as soldering points for lead wire attachment. A typical radiative heat transfer gage comprises a disc-shaped substrate with one resistance element deposited on each face. The long dimensions of the two elements are at a right angle to one another to minimize shadowing of the lower element by the upper. Radiant and convective heat flux is sensed by the upper element, and only radiant flux by the lower. Figure 18 is a photograph of a typical gage.

Dielectric substrates are normally used with polished surfaces which result in bright, specular platinum films. Absorption of incident radiant energy by such films would obviously be expected to be rather low. Nevertheless, because of known electrical characteristics of these platinum films[3] and by virtue of lengthy experience of CAL with the preparation and use of these films, the application of the platinum films to measuring radiant flux was deemed desirable.

Ideally, the resistive films would absorb all wavelengths equally and the substrates would be perfectly transparent to the radiation spectrum of interest. Realistically, it is necessary to compromise by selecting materials with favorable characteristics in the wavelength region of interest. Since it was decided to use the platinum film, only the choice of a substrate remained. Because a firing temperature of 1000 to 1400° F is required to produce the platinum films, the three most likely substrate candidates were pyrex, fused quartz and synthetic sapphire. Of principal concern is the spectral transmission in the infrared and the near infrared. Table I compares the transmission characteristics of these three materials relative to black body radiation at three typical source temperatures.

*Liquid Bright Platinum Solution #05-X, Hanovia Liquid Gold Division, East Newark, New Jersey

TABLE I

Optical Transmission of Pyrex,
Fused Quartz and Synthetic Sapphire

Material (~1/16" thick)	Approx. Passband (50% points) microns	Approximate Percentage of Total Black Body Radiation Transmitted 1360°R	2260°R	3160°R
Pyrex	0.32 - 2.7	14	48	66
Fused Quartz	0.20 - 4.0	32	66	82
Synthetic Sapphire	0.20 - 6.0	61	85	93

Synthetic sapphire, with its broad spectral passband, appeared most appropriate; but difficulty in effecting a suitable bond with the platinum film developed.* This problem, coupled with a lack of reliable data on the temperature dependence of the thermal properties of sapphire (required to convert surface temperatures to heat flux), led to the decision to use fused quartz. Thermal properties of clear, fused quartz had already been experimentally evaluated at CAL.[7]

*The best bonds are obtained when substrate softening occurs near the firing temperature (as in pyrex). A slight surface etch would probably improve the quality of bonds for such high melting point materials as sapphire.

CALIBRATION

A. Objectives

The principal objective of the calibration program was to determine the spectral absorption of Hanovia 05-X platinum films deposited on fused quartz* substrates. Because of their relative ease of measurement, measurements of the spectral reflection and transmission characteristics were made instead. From these data, spectral absorption results were obtained since the sum of the energy components reflected, transmitted and absorbed must equal unity.

Additional intermediate objectives involved the determination of:

a. Spectral reflection and absorption ascribable to the fused quartz substrate

b. Spectral reflection and absorption ascribable to the magnesium fluoride coating**

c. Dependence of thin-film optical properties on position relative to incident energy: (1) on front surface of substrate, (2) on rear surface of substrate

d. Dependence of thin-film optical properties on angle of the incident energy

e. Dependence of thin-film optical properties on tolerances associated with fabrication techniques

For applications to the base heating program, peak radiative energies were taken to lie between wavelengths of one and two microns. Accordingly, measurements were made in the range from 0.8 to 2.6 microns with the long wavelength limit set by deteriorating transmission characteristics of the refracting-type monochromator and a decreasing sensitivity of the infrared detector employed.

B. The Test Specimens

Test specimens were prepared using fused quartz discs that measured 0.375-inch in diameter and 0.0625-inch in thickness. Whereas the resistance elements are made in the form of narrow strips, the appropriate test specimens had one surface completely platinized to alleviate

*General Electric Company, Type 101

**As routine practice, all CAL thin-film resistance elements are overcoated with a 0.1-micron film of magnesium fluoride to provide mechanical protection and electrical insulation.

critical optical alignment problems (see Fig. 18). Special precautions were taken to make the specimen films as representative of typical heat-transfer gages as possible. Visual examination of the "mirror" samples revealed an obvious variation in the optical density resulting from the brushing technique of applying the platinic solution. A similar degree of density variation in standard heat-transfer gages is observed.

A total of ten specimens was prepared consisting of:

1 clear, fused quartz blank
1 fused quartz blank, MgF_2 coated one side
3 quartz blanks, platinum film on one side
5 quartz blanks, platinum film on one side, MgF_2 coated both sides

Several of the fluoride-coated specimens developed a mottled surface that precluded their use. The cause of this effect, which was associated with the coating, was not determined.

C. Test Apparatus

A source of radiant energy, external transfer optics, a monochromator, a light chopper and an infrared sensor constituted the main elements of the test apparatus. For the wavelength region of interest, a tungsten filament represented a satisfactory radiation source, and a 32-candlepower, 6-volt lamp operated on direct current was used. An image of the lamp filament was formed in the plane of the entrance slit of the monochromator by a 3-inch diameter, 18-inch focal length spherical mirror. A sector-wheel chopper, placed near the focal end of the optical beam, generated a square-wave signal permitting use of a-c amplification.

The monochromator was a Gaertner unit that uses quartz refracting optics with an attendant long wavelength limit of 3 microns. A lead sulphide detector, with an infrared cut-off of approximately 3 microns, was employed at the exit slit. Detector output was manually recorded from a visual display on a calibrated Tektronix 502 oscilloscope.

A calibration of the wavelength scale of the monochromator was performed using the prominent lines in the mercury spectrum in the range from 0.546 to 2.34 microns. Following a mechanical adjustment of the wavelength scale, no corrections to dial readings were required.

Linearity of detector output with light flux input was evaluated by recording the signal as a function of entrance slit width. For the range of signal levels recorded in the subsequent tests, no linearity corrections were required.

D. Transmission Measurements

Measurement of specimen spectral transmission was a rather simple experimental endeavor. The arrangement of components is shown schematically in Fig. 1a. Data were taken by recording the detector output at some specific wavelength with the specimen alternately in and out of the optical beam. Thirteen test points in the wavelength interval from 0.8 to 2.6 microns were sampled. Insertion of the specimens into the optical beam was accomplished manually in a manner that did not guarantee that the same unique area of the specimen was sampled each time. With optical beam dimensions approximating 1mm by 3.5mm at the plane of the specimen insertion, some scatter in transmission data resulting from non-uniform optical density of the platinum films could be anticipated. By this means, an averaging of the data was obtained.

The problem of scattering of the light energy due to traversal of the specimen was investigated. Relative transmission readings were recorded as the distance between the entrance slit and the specimen was varied. As would be expected, the measured relative transmission decreased with increasing distance of the specimen from the slit. Since the measured effect amounted to a few tenths percent for a separation of seven centimeters (nominal separation amounted to only two cms), scattering effects on measured data were insignificant.

E. Reflection Measurements

Measurement of spectral reflection was made relative to a standard reflecting surface (one of known characteristics). In this method it is necessary to reflect the optical beam alternately from the test specimen and from the standard surface. Component alignment problems thus become critical since false readings will result if the standard and the specimen are not precisely positioned in the same relative angular orientation to the beam.

To facilitate alignment, a special jig was fabricated. A right circular cylinder, supporting the specimens, was mounted coaxially on an indexing head that permitted repeating rotational position settings. Four flat surfaces, oriented parallel to the cylindrical axis and spaced 90° apart about the circumference, were milled into the cylinder. Each flat was fitted with a flat plate supported on three spring-loaded, adjustable screws. One specimen was cemented in a centrally-located hole in each plate. Reflection data from either surface of the specimen could be taken simply by reversing the mounting plate.

A schematic of the component arrangement employed for reflection measurements is shown in Fig. 1b. The arrangement is that corresponding to an angle of incidence of 45° relative to the normal; a somewhat modified scheme (not shown) was used for 15° incidence and represented the smallest angle physically realizable with this particular apparatus.

EXPERIMENTAL RESULTS

A. General

Some introductory comments are pertinent at this point to place the test results in proper perspective.

A marked lack of consistency is to be found in the literature in the definition of the terms reflection, transmission, and absorption. Figure 2 defines the context in which the subsequent test data are given. This illustration indicates the several parts into which the incident energy separates for the case of normal incidence (zero degrees incidence relative to the surface normal). The collinearity of all the energy components is in contrast to the non-normal incidence test conditions for which multiply-reflected images occur. Where the secondary images were resolvable from the primary and were of measurable intensity, individual measurements of each image were made and summed to yield a net reflection value.

The reflection measurements were of the relative type and required a known reflection standard. Lacking such a standard surface, a quantity of first-surface, aluminized mirrors were tested and that one with the highest reflection was selected as the reference. Since the best aluminized surface does not reflect 100% of the incident energy, a correction is required. All measurements were corrected therefore in accordance with the published spectral reflection of an aluminized surface[8] given in Table II.

Thus the numerical values of all the data are subject to the presumption that the reference mirror approximated a perfect aluminized reflecting surface. This one factor constitutes the major uncertainty in the data.

A flat, tungsten-ribbon filament is a desirable source of radiant energy for tests of this type. By optical selection, a central area of the filament is isolated and may be relied upon as of uniform radiance. Unavailability of a ribbon-filament source necessitated the use of a coiled-filament lamp. A very sharp gradient in source radiance was apparent when the filament image was scanned across the monochromator slit. This factor made alignment of the specimens so critical that the vernier adjustments on the indexing head were not sufficiently precise to obtain satisfactory repeatability of data. Instead, it was necessary

TABLE II

Spectral Reflection of Evaporated Aluminum

Wavelength, microns	% Reflection
0.80	86.3
0.85	85.8
0.90	88.9
0.95	91.8
1.00	93.8
1.20	96.0
1.40	96.7
1.60	96.9
1.80	97.1
2.00	97.2
2.20	97.2
2.40	97.2
2.60	97.3

to position the specimens for maximum signal by reference to the oscilloscope display.

Reflection measurements for platinum films on the rear surface of a substrate are plagued by the existence of multiple images. For 45° incidence, three distinct images could be observed at the monochromator entrance slit, but only two were of measurable intensity. For the case of 15° incidence, the secondary image overlapped the primary to the extent that it was not resolvable for measurement. Thus all measured reflection data are probably low because of the inability to account for all the reflected energy. Because the internal reflection losses are minimized by decreasing incidence angle, the data at 15° are considered the more reliable.

As mentioned earlier, the useful long wavelength of both the detector and the manochromator is approximately three microns. This factor, coupled with the spectral intensity of the source, caused the measured data to be terminated at 2.6 microns. Low signal levels and poor signal-to-noise ratios make the results beyond about 2.2 microns subject to sizable errors.

For favorable signal-to-noise ratios, it was desirable to use maximum slit widths consistent with required spectral purity. Since the spectral reflection and transmission of platinum films of about 0.1-micron thickness are well-behaved functions, resolution requirements were modest. A 0.1mm slit width was used with a resulting resolution as shown in Table III.

B. Test Data

Both the measured (reflection, transmission) and the inferred (absorption) data are summarized in Figs. 3 through 17 in the form of a percentage versus wavelength. These Figures generally are self-explanatory, yet certain salient features warrant discussion.

Figures 3 and 4 relate to clear, fused-quartz specimens in both the coated and uncoated state. The absorption of radiant energy in both states averages about 2% and hence is negligibly small for all practical purposes. A common usage of magnesium fluoride is as a low-reflecting coating on optical surfaces. The effectiveness of low-reflection coatings

TABLE III

Resolution of the Gaertner Quartz Monochromator

Wavelength, microns	Resolution, microns/0.1mm
0.80	0.022
0.85	0.024
0.90	0.026
0.95	0.028
1.00	0.030
1.20	0.032
1.40	0.033
1.60	0.029
1.80	0.027
2.00	0.024
2.20	0.022
2.40	0.020
2.60	0.018

is a maximum when the thickness is equal to $\lambda/4n$, where λ is wavelength and n is the coating index of refraction.[9] For a 0.1-micron coating, the maximum effect would be realized at about 0.55-micron which is outside the range of measurement of these experiments; however, some slight reduction in reflection of the coated specimen may be seen at the shorter wavelengths (Fig. 4).

Figures 5 through 10 summarize data obtained with the three platinized but uncoated specimens. The relative effects of angle of incidence and orientation of the film relative to the incident radiation are shown. Transmission of the platinum films is very small, averaging one to two percent. Front-surface films show increasing absorption with decreasing angles of incidence. For rear-surface films, the converse is true. All specimens indicate that a rear-surface film has a higher absorption than a front-surface film. The reflection data show reasonably good agreement among samples with mean values for front-surface films of 72%, 74%, 82% at 45° and 72%, 70%, 72% at 15°.

Data applicable to platinized specimens coated on both surfaces with magnesium fluoride are included in Figs. 11 through 15. Because of a mottled surface that developed in the coatings of two specimens, only three units could be tested. The results corroborate the observations made above with respect to the uncoated specimens.

For practical purposes, the experimental results may be considered embodied in Figs. 16 and 17 where the spectral reflection of three coated and three uncoated specimens is compared at 15° incidence. Data for this test condition are considered most reliable, are most consistent, and probably are best representative of test environments. Mean absorption data used in reduction of experimental base heating measurements are listed in Table IV.

Thus, if $\dot{q}_k$ is the radiative heat transfer rate, $\dot{q}_c$ the convective heat transfer rate, $\dot{q}_f$ the rate measured by the front-surface gage, and $\dot{q}_r$ the rate measured by the rear-surface gage, then for a magnesium fluoride coated gage:

TABLE IV

Mean Absorption Data for Radiative Heat Transfer Gages in the Spectral Interval from 1.0 to 2.0 Microns

Type of Gage Surface	Film Location	Absorption (%)
Uncoated	Front surface	29
Uncoated	Rear surface	48
Coated (MgF_2)	Front surface	32
Coated (MgF_2)	Rear surface	40

$$\dot{q}_c = \dot{q}_f - \frac{0.32}{0.40}\dot{q}_r$$

$$\dot{q}_k = \frac{\dot{q}_r}{0.40}$$

For a non-absorbing substrate, an increased absorption for a rear-surface over a front-surface film is predictable from theory. Because of multiple-image problems associated with reflection measurements from rear-surface films, the possibility was considered that these absorption data could be high if the reflection data were low. Accordingly, a simple, qualitative check was performed using photographic flash bulbs as radiant sources. These results demonstrated conclusively that the highest output from a thin-film resistance element was obtained when that film was on the rear surface of the substrate relative to the flash bulb.

Results on the absorption of thin platinum films included in this report apply to room temperature conditions. Reference to the standard sources and handbooks showed no data on the effects of ambient temperature on the optical properties of thin films, and unfortunately the present experimental arrangement was not adaptable to the use of heated specimens. Measurements of radiative heat flux to surfaces maintained at temperatures as high as 1000°F have been made. Appendix A is a commentary on the interpretation of such measurements in a situation where calibration data are non-existent.

CONCLUSIONS

Subject to the qualifying remarks that have preceded concerning the experimental procedures and components, the following itemized conclusions derive from the test results:

1. Absorption within the fused quartz substrate is negligibly small. Reflection is typical of naked glass surfaces.
2. Effects of thin dielectric films like magnesium fluoride must be evaluated in conjunction with the base (substrate) material. Whereas the presence of such films on clear, fused quartz has negligible impact on the optical characteristics, their presence on platinized samples of quartz does show pronounced effects.
3. Platinum films on the rear surface of the substrate absorb more radiant flux than those on the front surface.
4. The optical properties of the film-substrate composite are relatively uniform in the wavelength range from 1.0 to 2.2 microns.
5. For front-surface films, the absorption increases with decreasing angles of incidence; for rear-surface films the converse is true.
6. The apparent effect of the magnesium fluoride coating is to increase absorption in the front-surface film and decrease absorption in the rear-surface film.
7. Transmission of the platinum films is uniformly low.
8. Variability in the optical characteristics ascribable to fabrication techniques is generally small.

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APPENDIX A

Radiative Heat Transfer Measurements at Elevated Ambient Temperatures

One of the important parameters in rocket base heating studies conducted at CAL is the recovery temperature of the reversed flow.[1] This quantity may be determined by making measurements of heat flux to heated surfaces and extrapolating the data to a temperature at which the heat flux would be zero. Maximum ambient temperature of the instrumentation is usually about 1000°F, and radiative as well as convective heat flux components are desired. Since radiative gages are calibrated at room temperature conditions, the problem of data interpretation for measurements made at elevated temperatures occurs. This appendix briefly discusses the interpretation problem.

Construction features of the radiative heat transfer gages limit their applications to ambient temperatures of about 300°F. A special high-temperature, pyrex-type gage has been developed[3] that is usable for continuous operation at 1000°F. Radiative heat flux measurements at such temperatures are made using these special gages. Convective and radiative heat flux is sensed by gages flush-mounted in the rocket model base and only the radiative flux is sensed by similar gages installed behind clear, fused-quartz windows.

The only significant difference between the surface gage and the submerged gage, insofar as radiative flux is concerned, is the presence of the intervening fused-quartz window. Since the platinum films in all cases are on the front surface (relative to the incident flux) and at approximately the same temperature, there should be no appreciable difference in sensitivity to the incident radiative flux. To a first approximation it should be necessary only to compensate for the fused-quartz window.

The external transmission, I/I_o, of a slab of optical material is given by Equation 1.

$$I/I_o = (1 - r)^2 \, e^{-\alpha \chi} \tag{1}$$

r = surface reflectivity

α = absorption coefficient

χ = thickness of slab

Surface reflectivity is a function of material index of refraction which varies with the wavelength of the radiation.

$$r = \left(\frac{1 - n}{1 + n} \right)^2 \tag{2}$$

n = index of refraction

In the wavelength interval from 1 to 2 microns, the mean value of the index of refraction for fused quartz is 1.444. Variation of index of refraction of fused quartz with temperature is very small and amounts to less than 1% for a change of 1000°F. Thus, the mean value for n given above may be used with confidence for all hot base plate conditions.

Reflection loss at a glass-air surface, calculable from Equation 2, is 3.3%. Since the quantities α and χ in Equation 1 are both small in magnitude, the term exp $(-\alpha\chi)$ may be taken equal to unity. The external transmission of the fused quartz window in the 1 to 2 micron band becomes 93.5% and agrees well with the measured data given in Figs. 3 and 4. The submerged gage therefore received 93.5% of the radiative heat flux incident on the surface gage. Convective heat flux is then given by Equation 3.

$$\dot{q}_c = \dot{q}_{sur.} - \frac{\dot{q}_{sub}}{0.935} \tag{3}$$

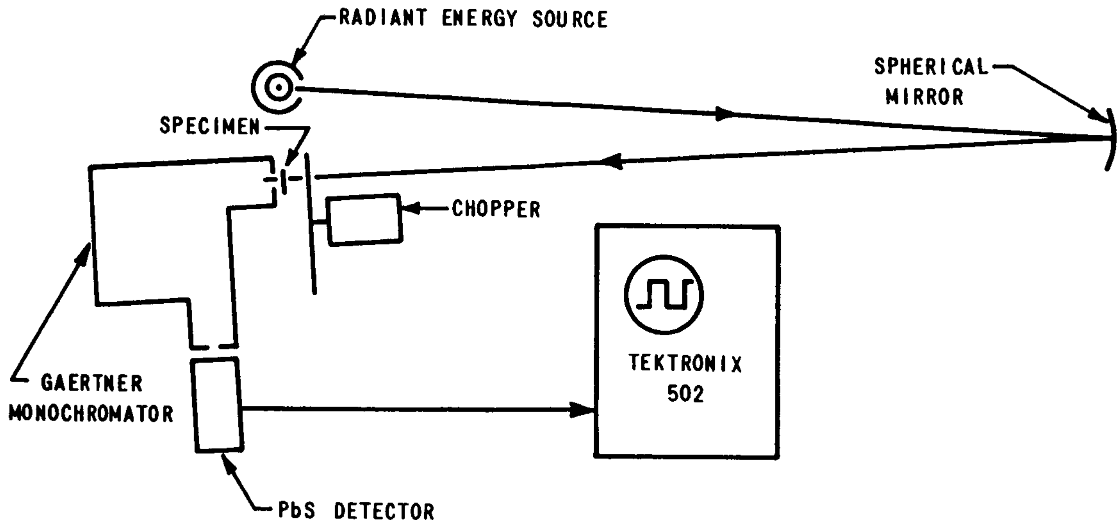
$\dot{q}_c$ = convective heat flux

$\dot{q}_{sur.}$ = net heat flux measured by surface gage

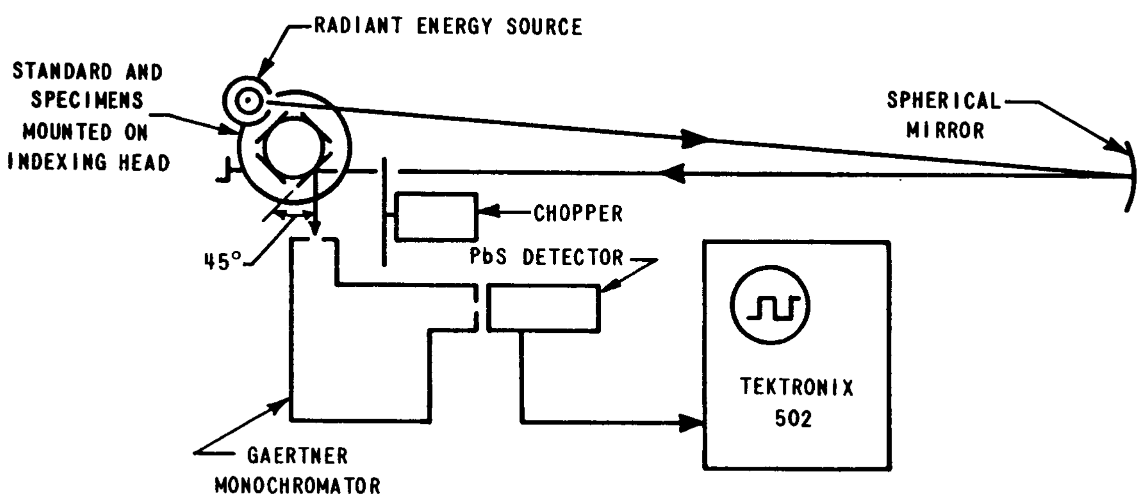
$\dot{q}_{sub.}$ = net heat flux measured by submerged gage

Although the fraction of the measured heat flux due to radiation is known, the actual value of the incident heat flux is not subject to a direct analysis since the optical properties of the films at elevated temperatures are not known. In the present situation, however, the problem is not hopeless.

Heated bodies radiate energy proportionally to the fourth power of their absolute temperature. If we take the rocket exhaust gas temperature as 2500°F, it is found that a gage at 1000°F will receive only 6% less net radiative heat flux than one at 70°F. Further, if the radiative heat flux is measured at room temperature conditions, where the platinum film response is known, the change in gage steady-state (base plate) temperature will have very small effect on this quantity, all other conditions being held the same. Thus, radiative heat flux need be measured only at cold base conditions and can be taken as sensibly constant for hot base conditions up to 1000°F.



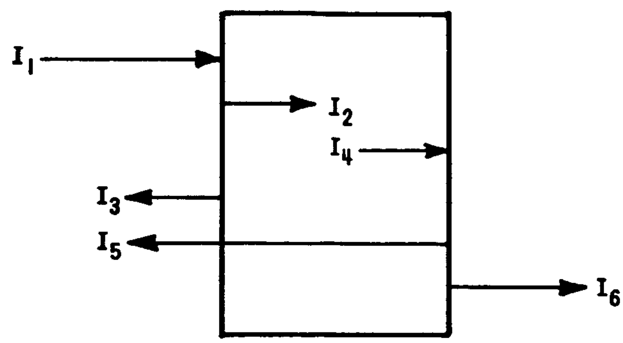
(a) APPARATUS ARRANGEMENT FOR MEASUREMENT OF TRANSMITTED ENERGY



(b) APPARATUS ARRANGEMENT FOR MEASUREMENT OF REFLECTED ENERGY

Figure I

DEFINITION OF TERMS



I_1 = INCIDENT ENERGY

I_2 = ENERGY ENTERING FRONT FACE OF SAMPLE

I_3 = ENERGY REFLECTED FROM FRONT FACE OF SAMPLE

I_4 = ENERGY INCIDENT ON REAR FACE OF SAMPLE

I_5 = ENERGY REFLECTED FROM REAR FACE OF SAMPLE*

I_6 = EMERGENT ENERGY

$$T = \text{TRANSMISSION (\%)} = \frac{I_6}{I_1} \times 100$$

$$R = \text{REFLECTION (\%)} = \frac{I_1 - I_2 + I_4 - I_6}{I_1} \times 100 = \frac{I_3 + I_5}{I_1} \times 100$$

$$A = \text{ABSORPTION (\%)} = \frac{I_2 - I_4}{I_1} \times 100$$

$$T + R + A = 100\%$$

Figure 2

*SUBSEQUENT FRONT FACE LOSS IS IGNORED

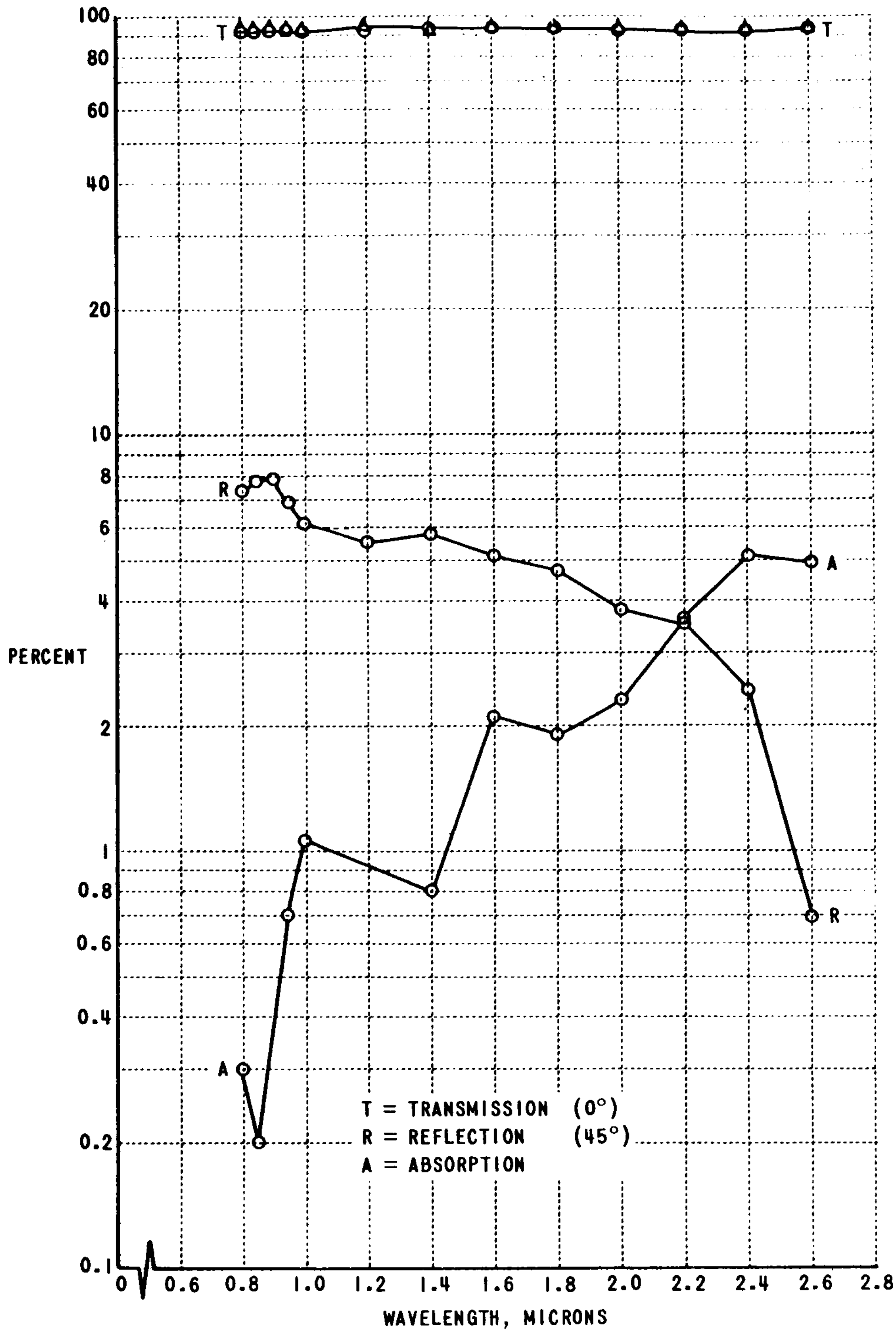


Figure 3 OPTICAL CHARACTERISTICS OF CLEAR, FUSED QUARTZ

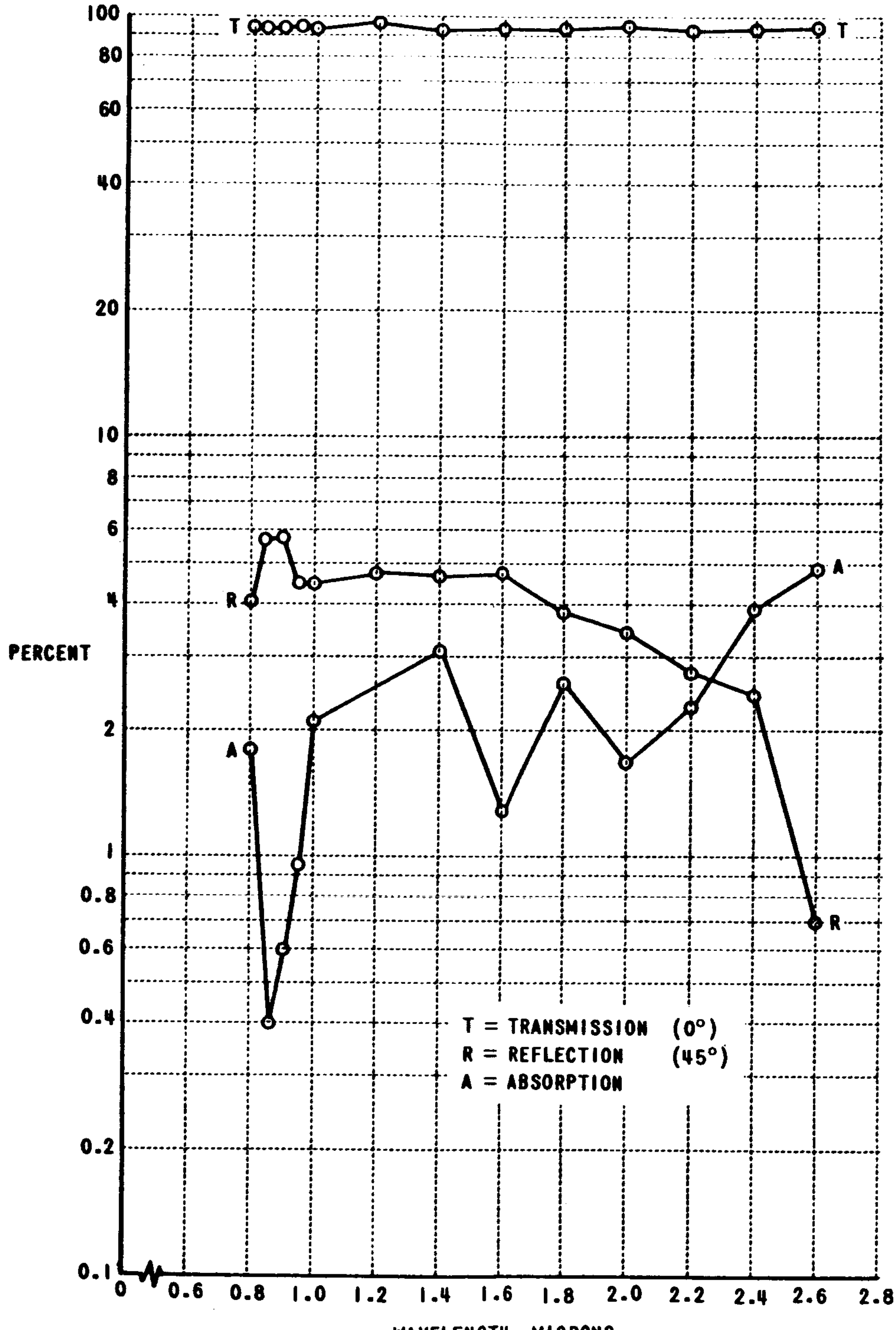


Figure 4 OPTICAL CHARACTERISTICS OF CLEAR, FUSED QUARTZ WITH MgF_2 COATING ON ONE SURFACE

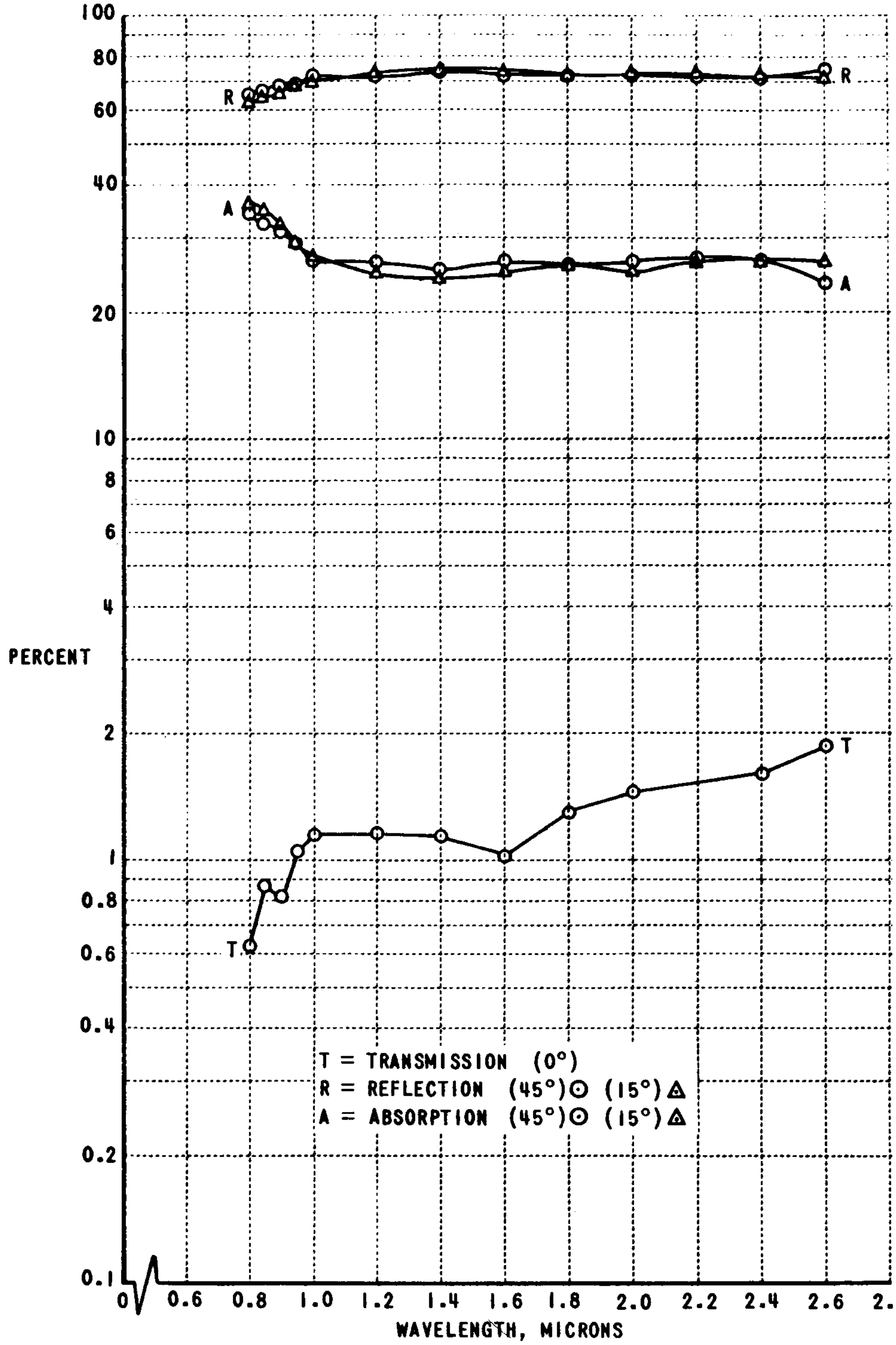


Figure 5 OPTICAL CHARACTERISTICS OF FUSED QUARTZ SPECIMEN #3A (ONE SURFACE PLATINIZED, PLATINUM FILM ON FRONT SURFACE)

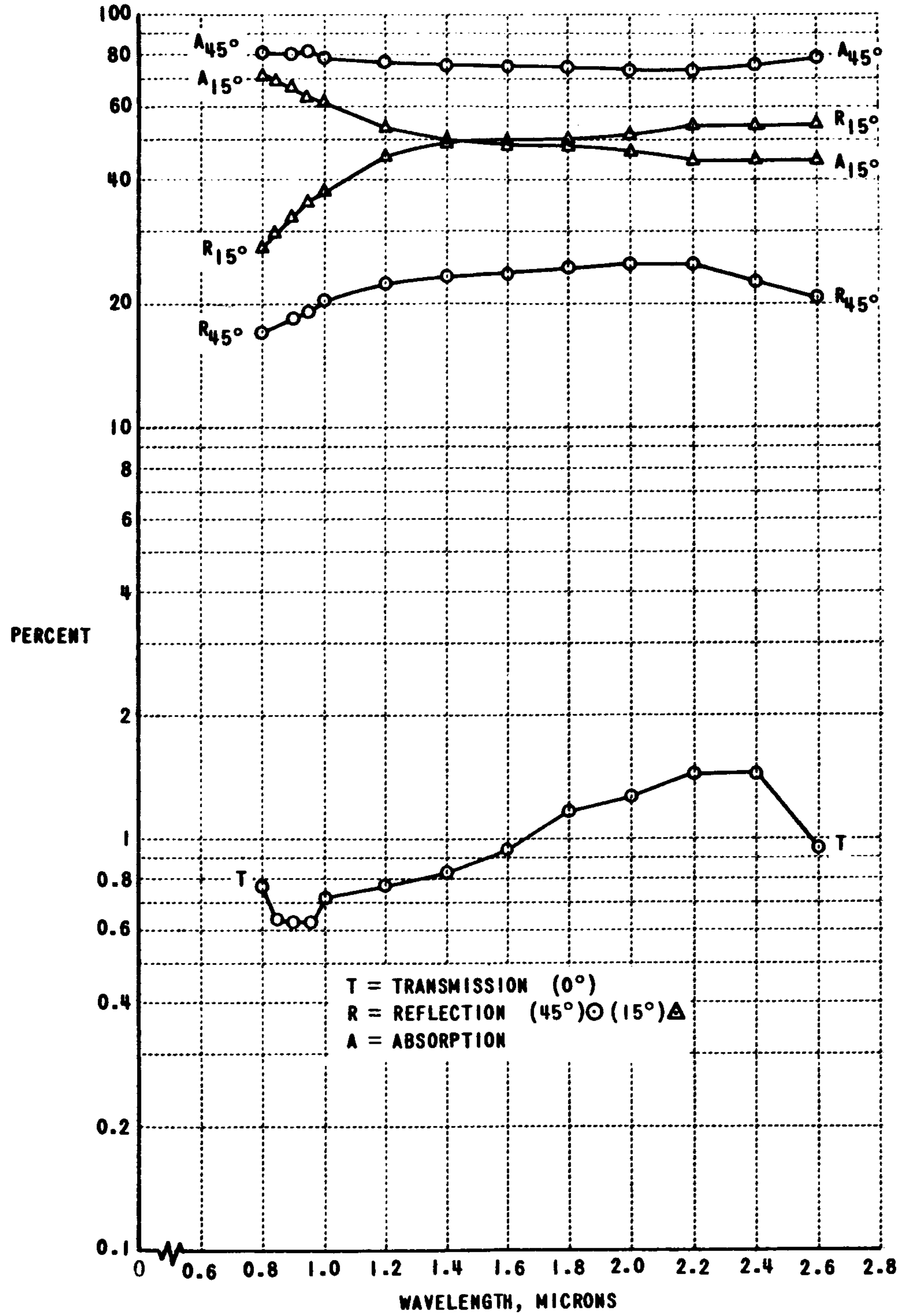


Figure 6 OPTICAL CHARACTERISTICS OF FUSED QUARTZ SPECIMEN #3B (SPECIMEN #3A ORIENTED WITH FILM ON REAR SURFACE)

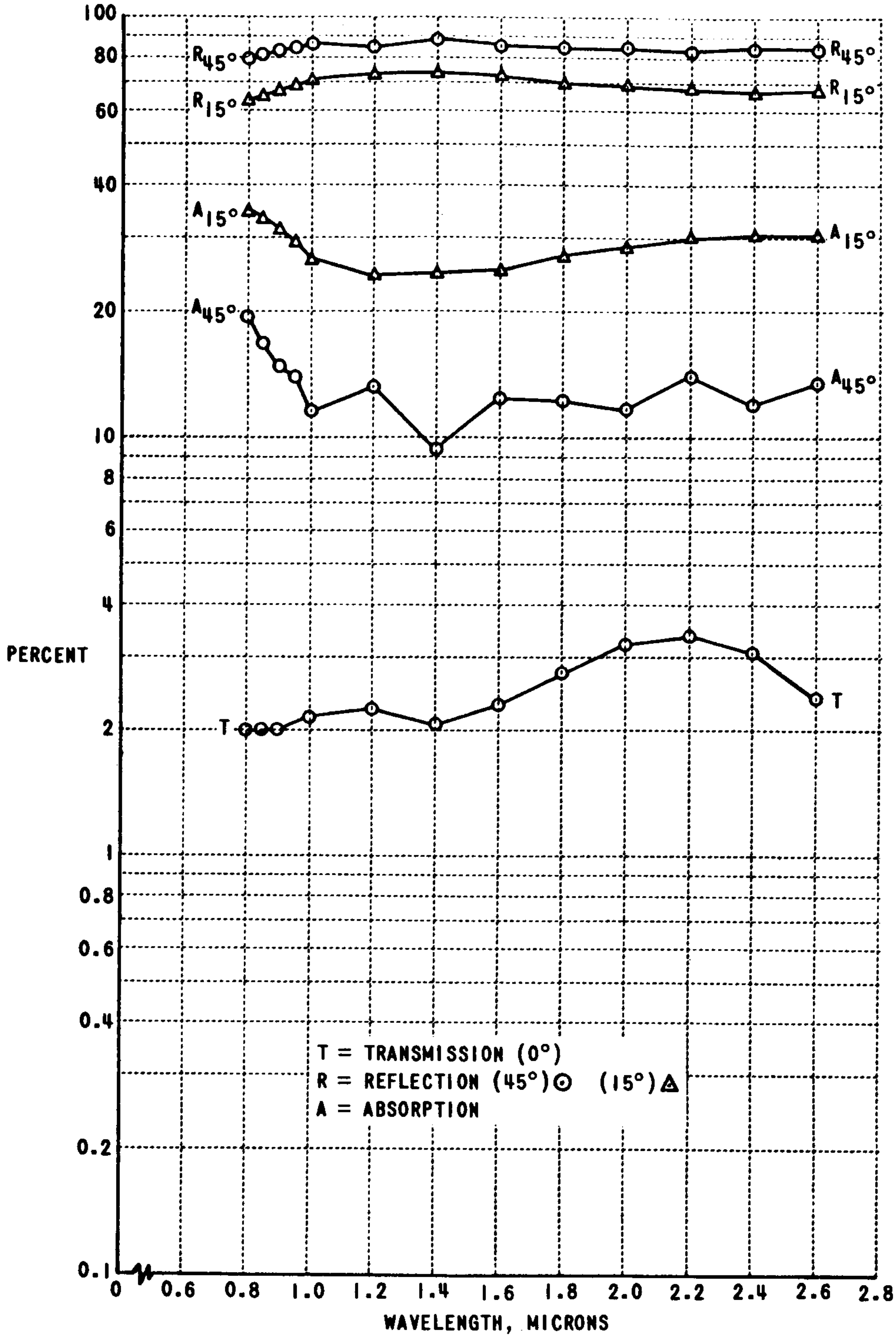


Figure 7 OPTICAL CHARACTERISTICS OF FUSED QUARTZ SPECIMEN #4A (ONE SURFACE PLATINIZED, PLATINUM FILM ON FRONT SURFACE)

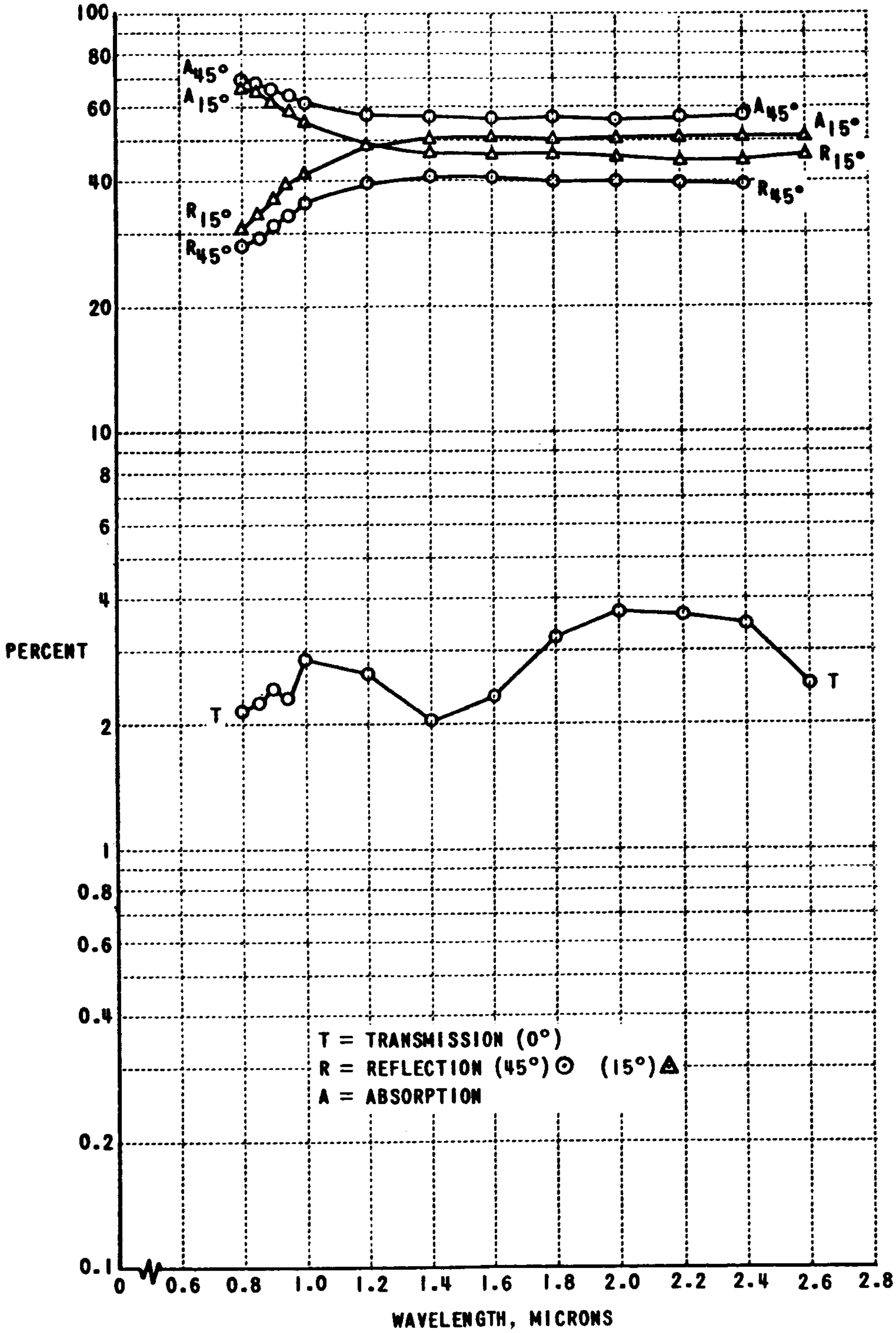


Figure 8 OPTICAL CHARACTERISTICS OF FUSED QUARTZ SPECIMEN #4B (SPECIMEN #4A ORIENTED WITH FILM ON REAR SURFACE)

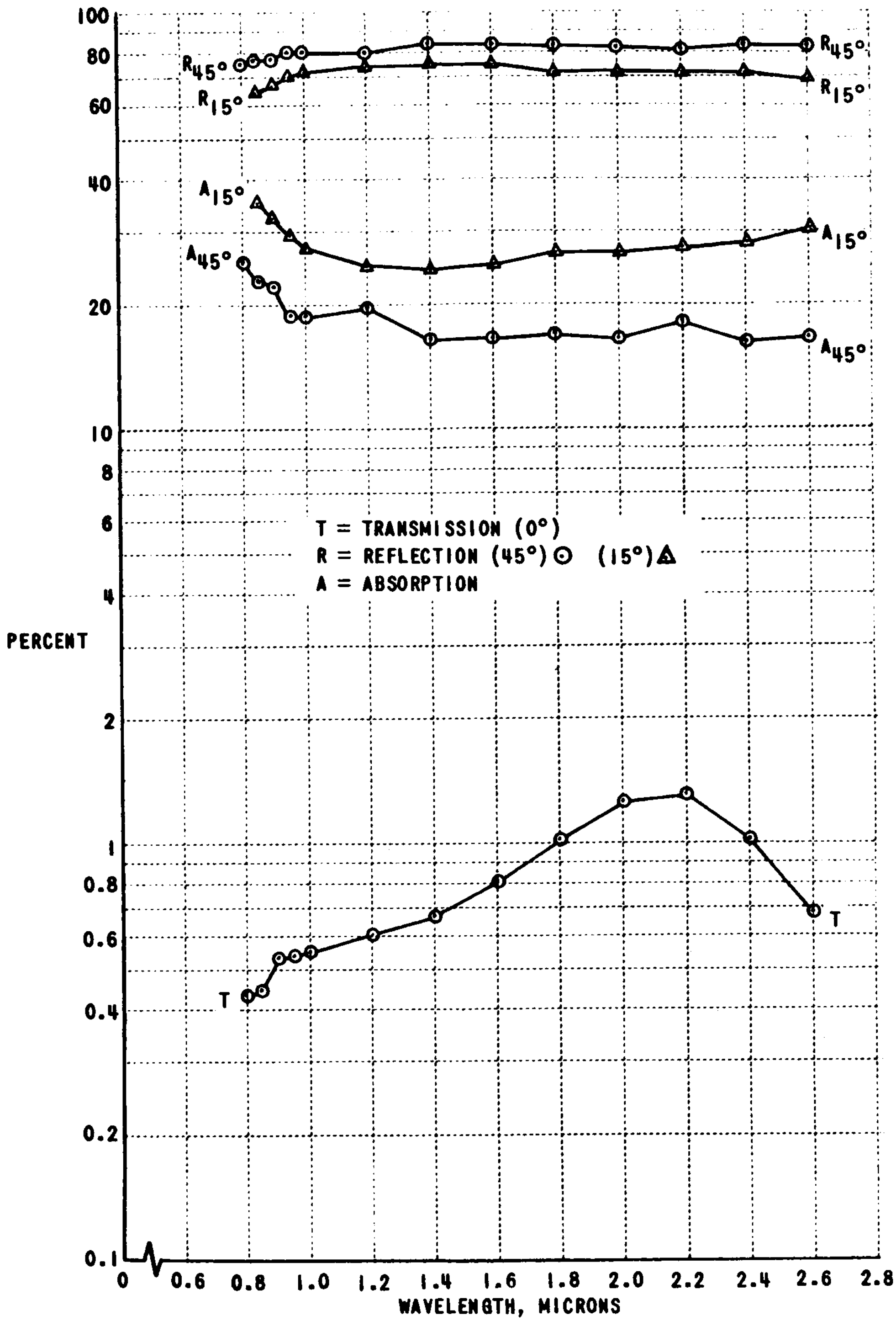


Figure 9 OPTICAL CHARACTERISTICS OF FUSED QUARTZ SPECIMEN #5A
(ONE SURFACE PLATINIZED, PLATINUM IN FILM ON FRONT SURFACE)

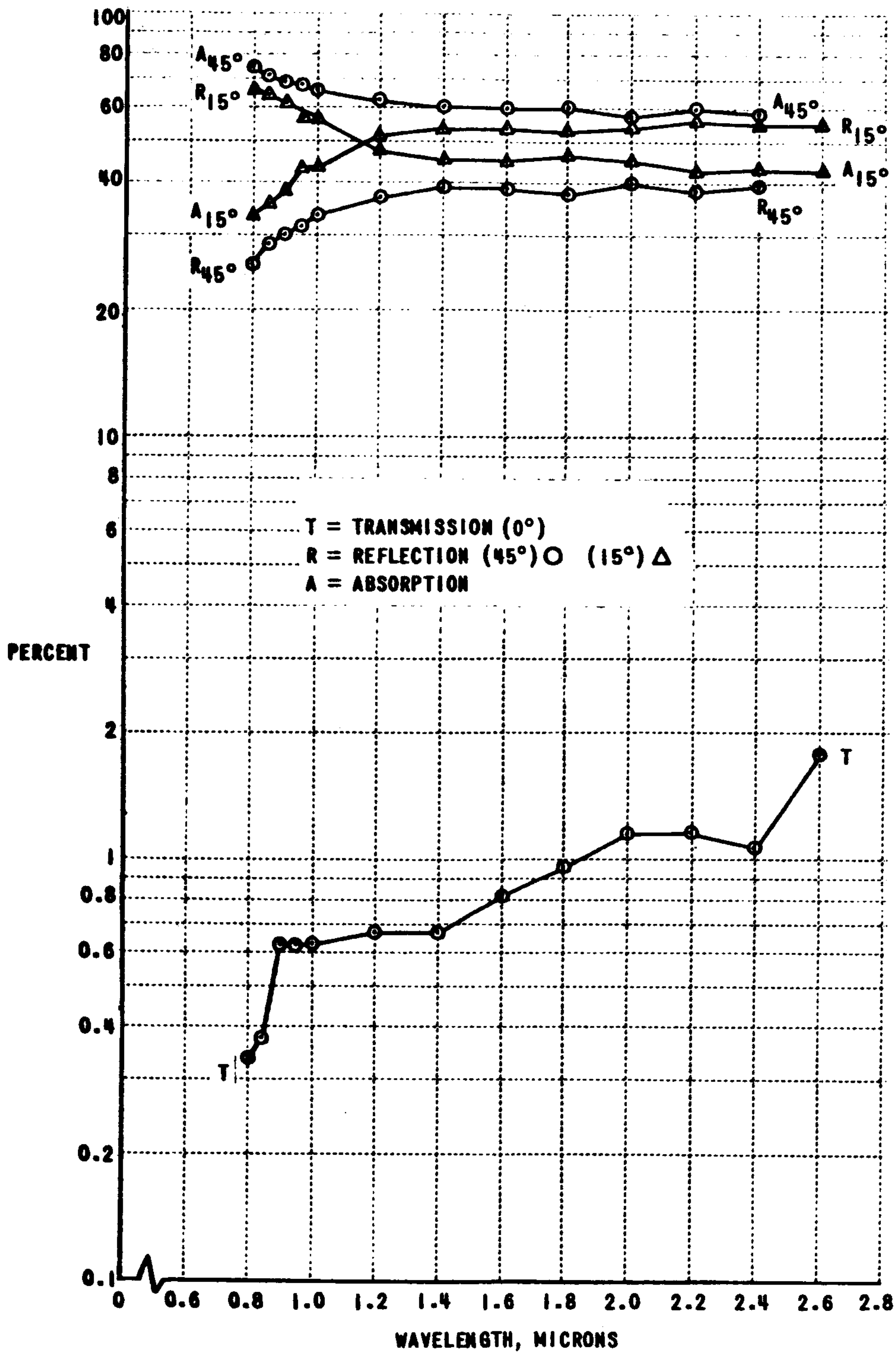


Figure 10 OPTICAL CHARACTERISTICS OF FUSED QUARTZ SPECIMEN #5B (SPECIMEN #5A ORIENTED WITH FILM ON REAR SURFACE)

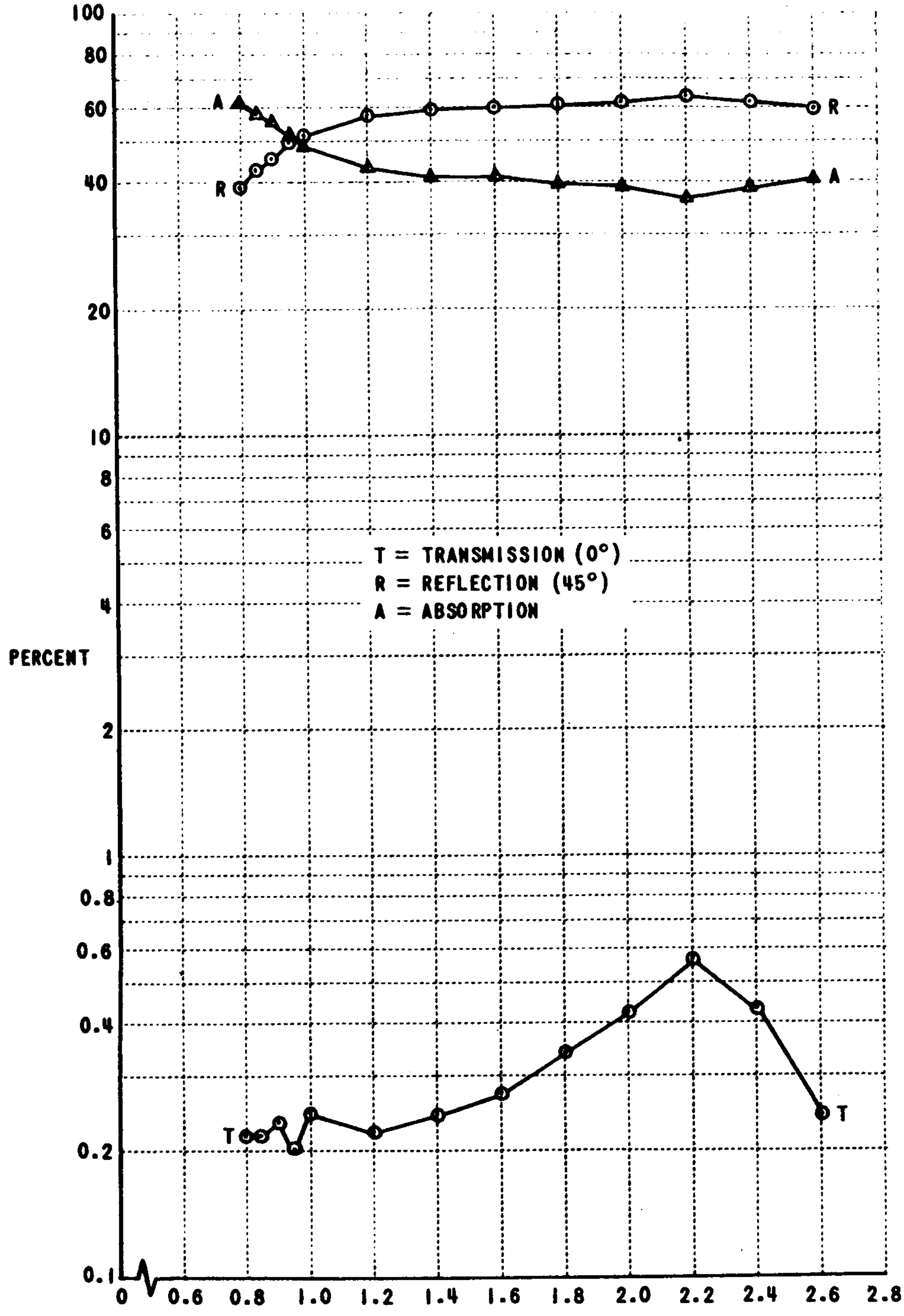


Figure 11 OPTICAL CHARACTERISTICS OF FUSED QUARTZ SPECIMEN #6 (ONE SURFACE PLATINIZED, MgF_2 COATING ON BOTH SURFACES, PLATINUM FILM ON FRONT SURFACE)

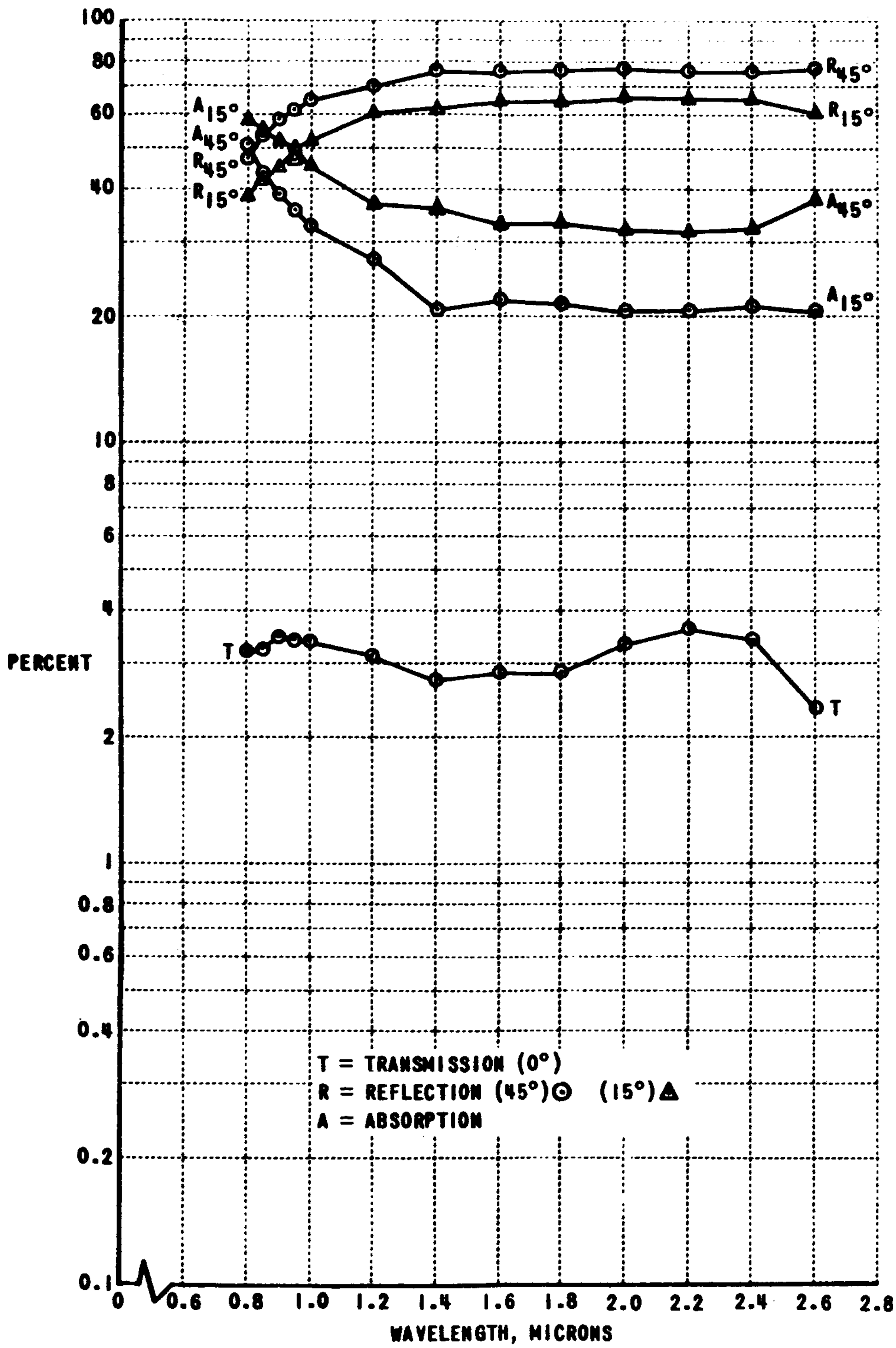


Figure 12 OPTICAL CHARACTERISTICS OF FUSED QUARTZ SPECIMEN #7 (ONE SURFACE PLATINIZED, MgF_2 COATING ON BOTH SURFACES, PLATINUM FILM ON FRONT SURFACE)

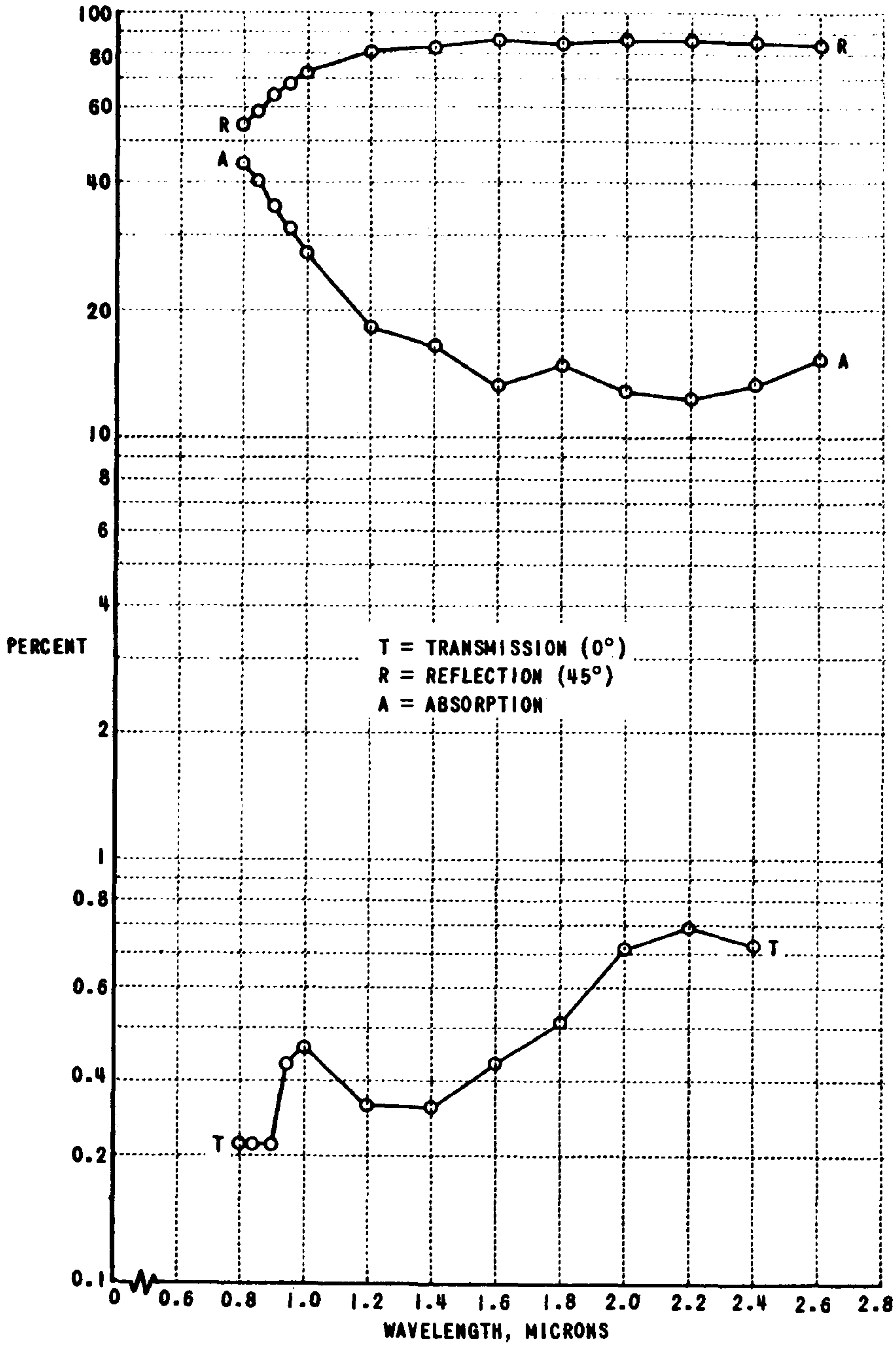


Figure 13 OPTICAL CHARACTERISTICS OF FUSED QUARTZ SPECIMEN #8 (ONE SURFACE PLATINIZED, MgF_2 COATING ON BOTH SURFACES, PLATINUM FILM ON FRONT SURFACE)

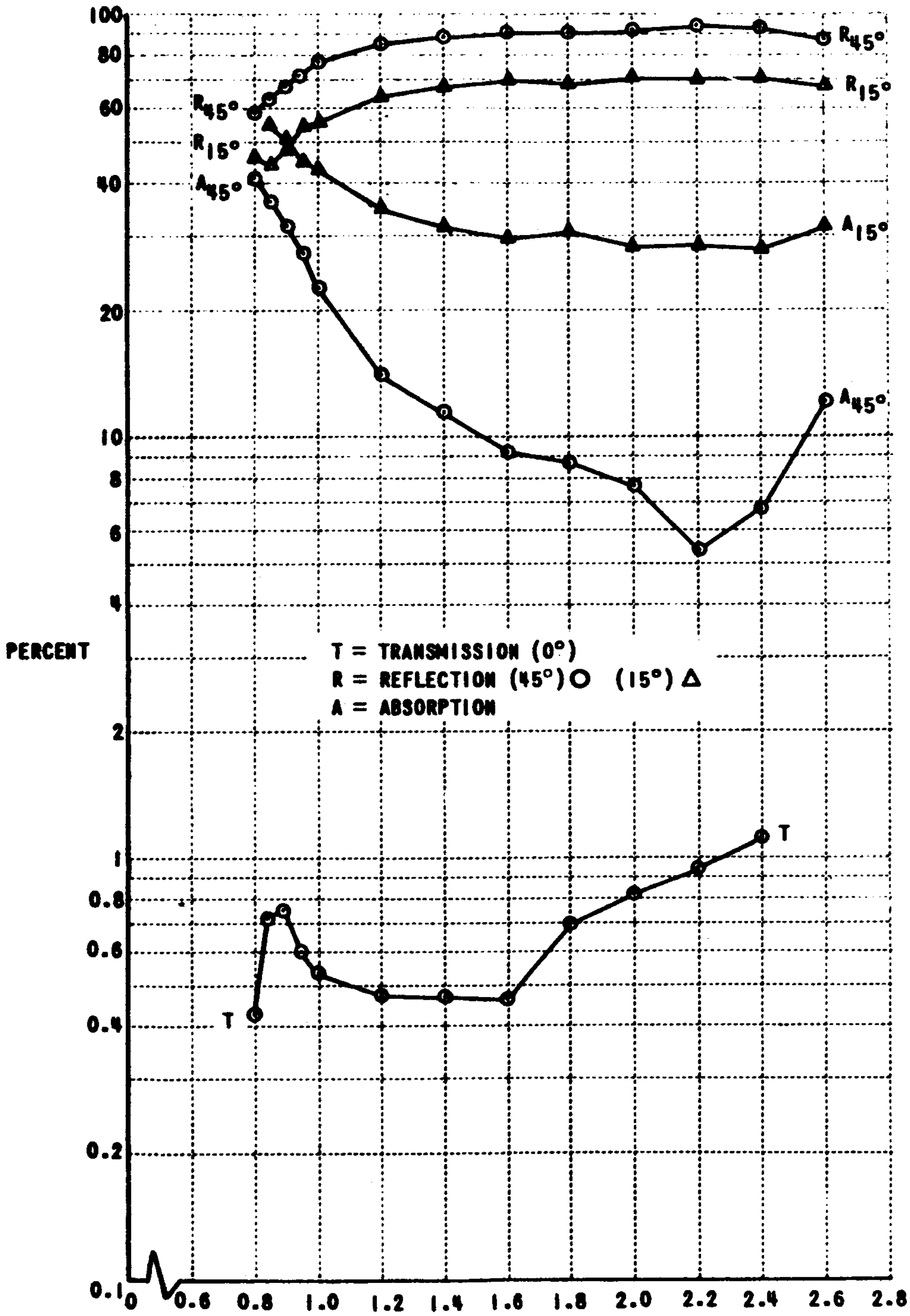


Figure 14 OPTICAL CHARACTERISTICS OF FUSED QUARTZ SPECIMEN #9 (ONE SURFACE PLATINIZED, MgF_2 COATING ON BOTH SURFACES, PLATINUM FILM ON FRONT SURFACE)

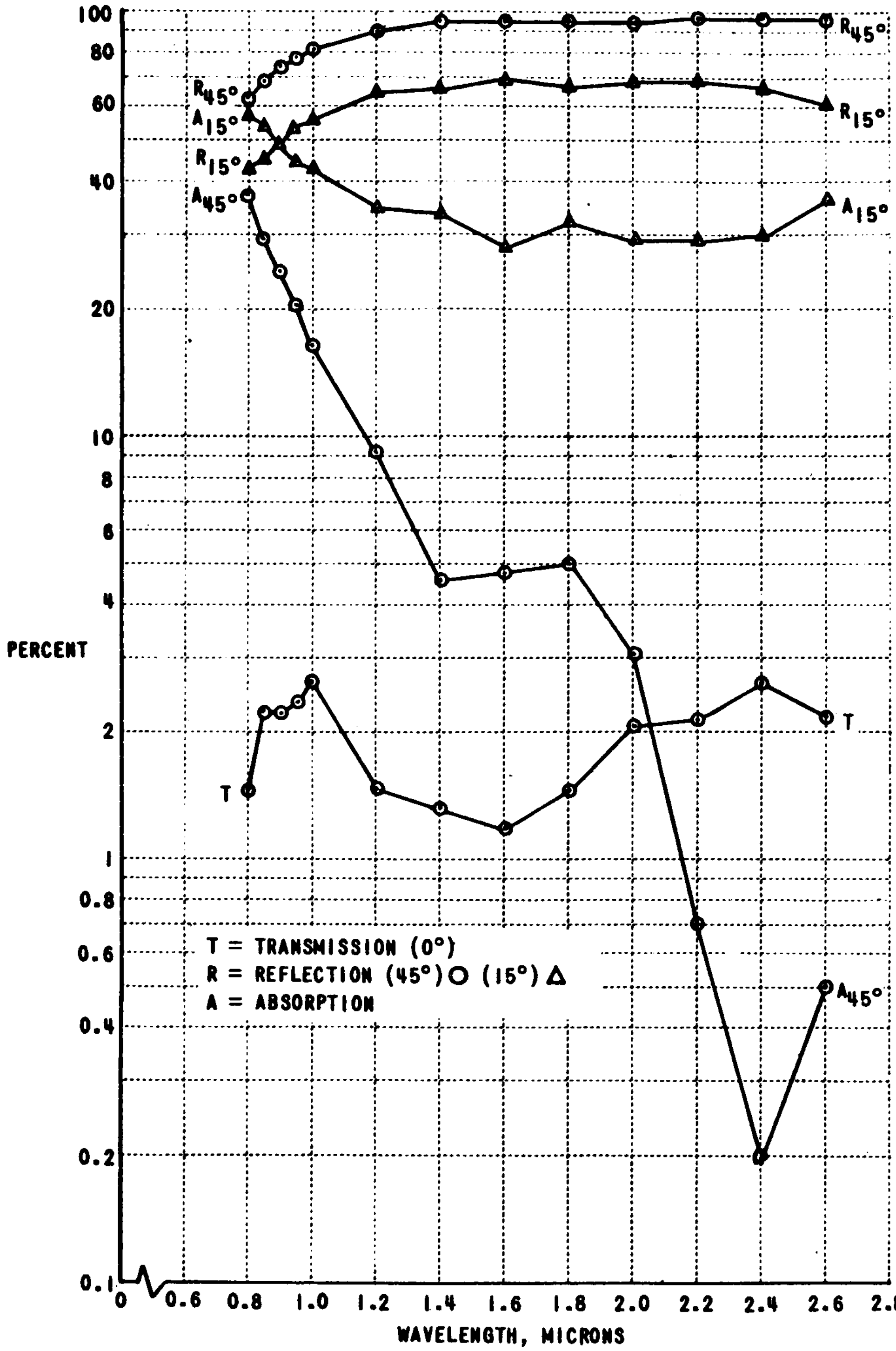


Figure 15 OPTICAL CHARACTERISTICS OF FUSED QUARTZ SPECIMEN #10 (ONE SURFACE PLATINIZED, MgF_2 COATING ON BOTH SURFACES, PLATINUM FILM ON FRONT SURFACE)

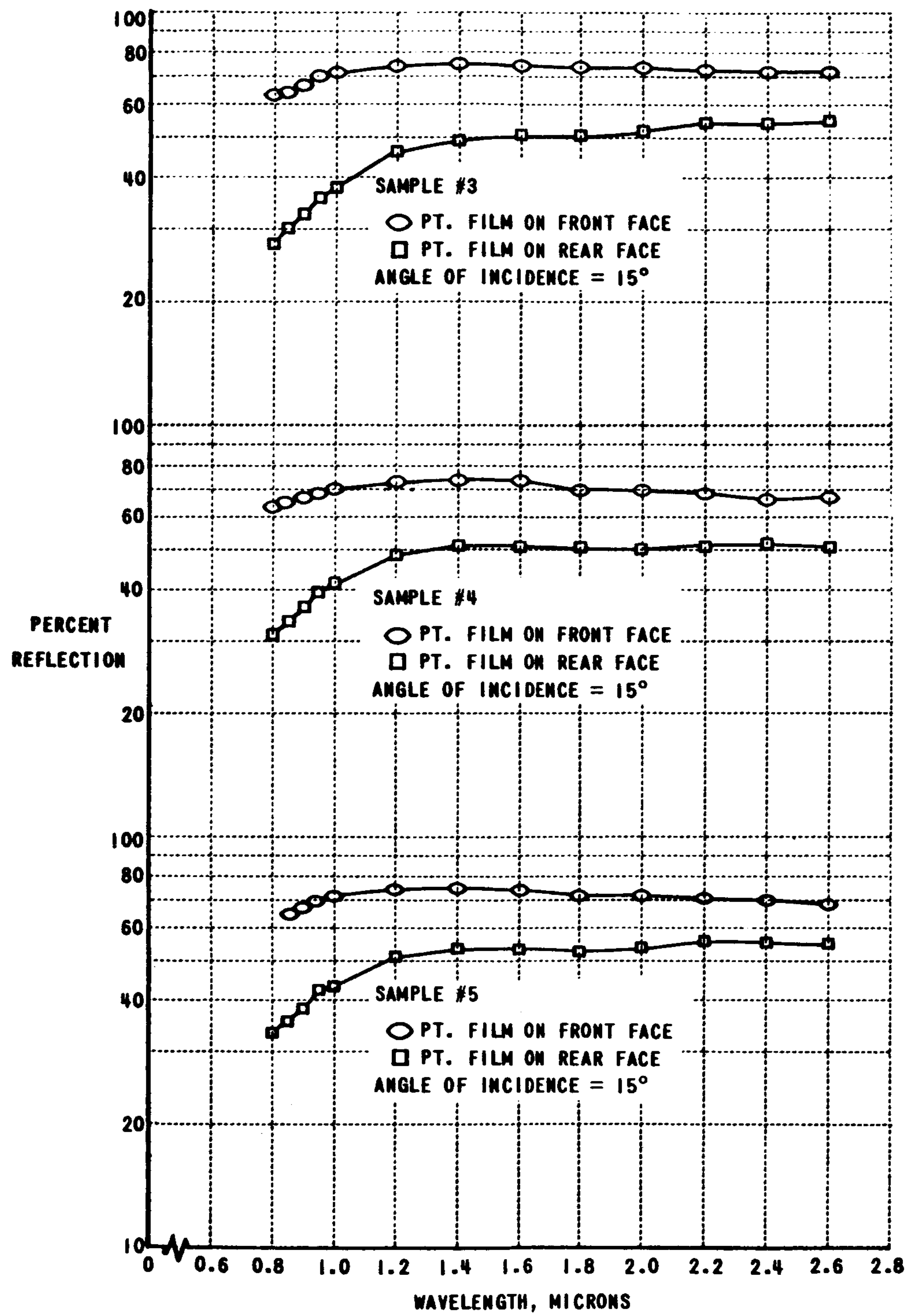


Figure 16 SPECTRAL REFLECTION OF PLATINUM FILMS ON FUSED QUARTZ SUBSTRATES

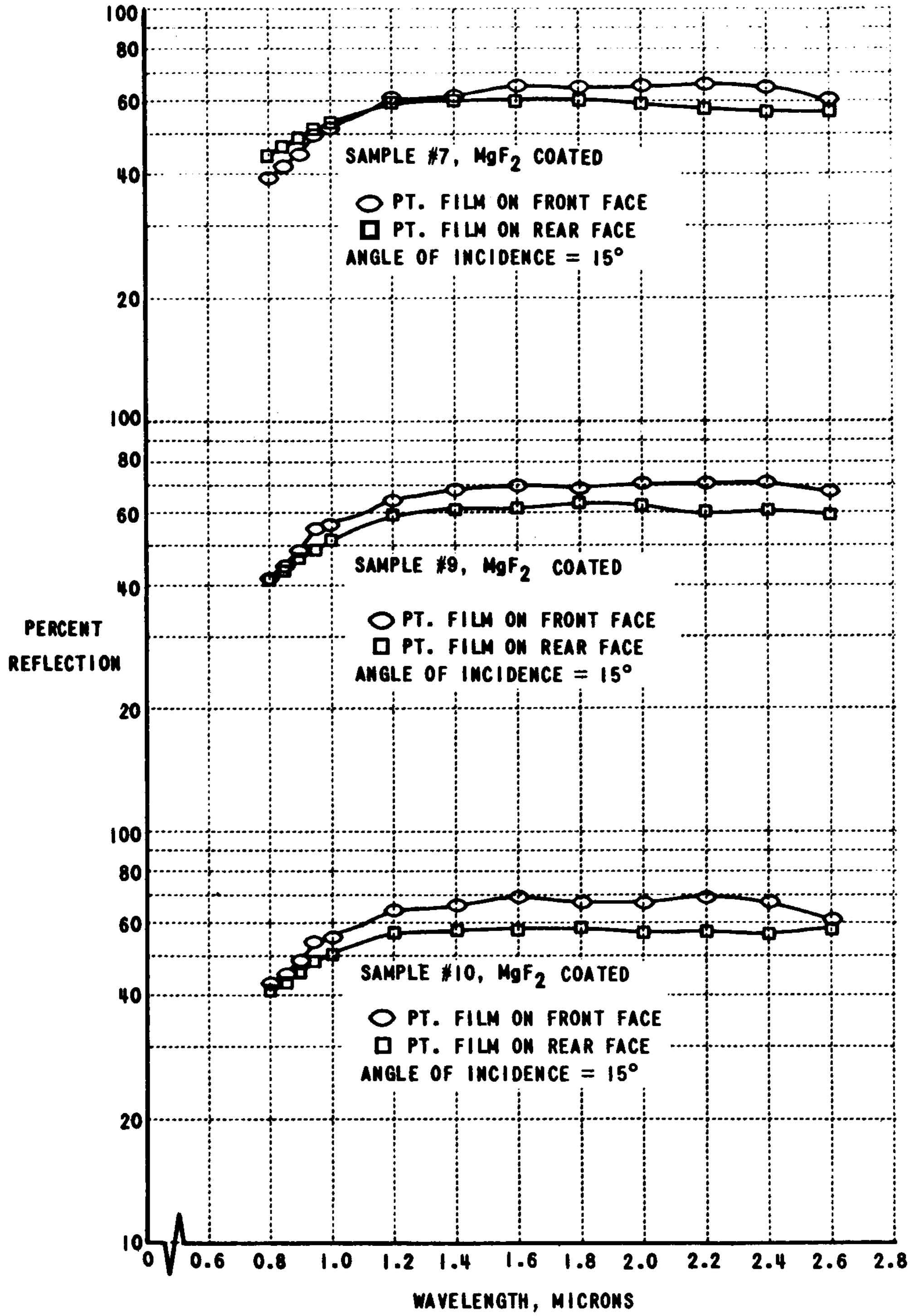
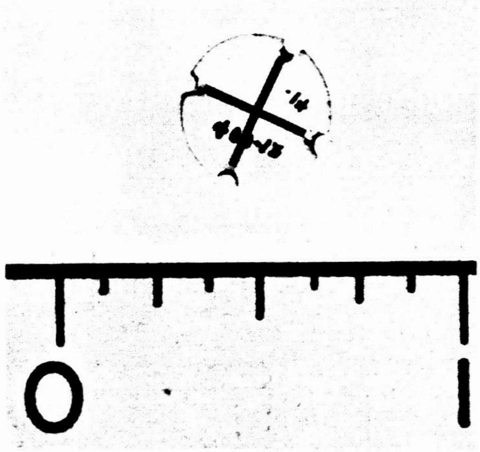
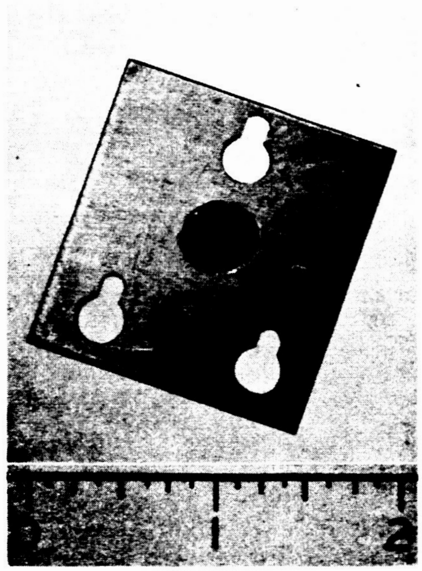


Figure 17 SPECTRAL REFLECTION OF COATED PLATINUM FILMS ON FUSED QUARTZ SUBSTRATES



RADIATIVE HEAT TRANSFER GAGE



TEST SPECIMEN IN HOLDER

Figure 18 TYPICAL RADIATIVE HEAT TRANSFER GAGE AND TEST SPECIMEN